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SUMMARY

A model for estimating the reliability of piping in nuclear power reactors is presented. This paper is the first of two papers describing the evaluation of primary coolant loop piping reliability. The second paper will discuss the simulation procedure in the assessment of the probability of piping failure (paper Division M #12/3). An application of the model in evaluating the influence of seismic events on primary piping reliability will be presented in paper J #6/6.

The modeling approach is based on the assumption that piping failures result from the growth of pre-existing surface cracks which were introduced during fabrication and welding. The flaw growth, due to the cyclic stress history, results from both operating transients and seismic events. Failure, as a consequence of crack growth, is predicted using the appropriate criteria for leak or fracture.

The initial length and depth distribution for cracks which exist at the onset of plant operation is characterized using a bivariate distribution as estimated from the literature. The probability of having a crack of any size in a given weld is estimated independently and is assumed to be a function of the volume of material under consideration. The influence of pre-service inspection enters through the probability of finding a defect of given length and depth. This detection probability, is also estimated from the literature. Thus, the initial crack population distribution is a function of the size distribution, existence probability, and inspection capability. The crack size distribution after inspection forms the initial conditions for the crack growth analysis.

Crack growth calculations employ a Paris type fatigue-crack-growth rate equation; $da/dN = CK'^{4}$. The coefficient C is a random variable with log-normal distribution which has been estimated from available data. A two-degree of freedom model allows for changes in the semi-elliptical aspect ratio by growth of each axis (surface length and depth) independently. The growth rate is controlled by an averaged stress intensity factor, $\Delta\overline{K}$, associated with each axis and evaluated for each class of transients. The transient and seismic stress histories are random processes. Nonuniform thermal stresses as well as residual stresses can be included.

Critical crack sizes for pipe leaks and complete pipe severances are evaluated using elastic, elastic-plastic, and fully plastic concepts. The leak rate is calculated from a linear-elastic crack opening displacement analysis; whereas, net section plastic instability is found to be the critical criteria for fracture. The probability of failure at a given location at a given time equals the probability of having a crack equal to or larger than the critical sizes associated with leak or fracture at that time. The probability of a leak or fracture can be assessed as a function of plant life.

1. INTRODUCTION*

Safety-related structures, systems, and components in commercial nuclear power plants are designed to withstand the combined effects of an earthquake and a large loss-of-coolant accident (LOCA). The combination of the most severe LOCA load with safe shutdown earthquake (SSE) loads was not controversial until about five years ago when the postulated LOCA and SSE loads were both increased due to improved analysis techniques and to account for such phenomena as asymmetric blowdown in pressurized water reactor (PWR) nuclear power plants. The combination requirement has therefore become more difficult to implement, particularly in the design of reactor pressure vessel internal and support systems. As a result, the U. S. Nuclear Regulatory Commission (USNRC) has initiated programs to establish a technical basis for reassessing the load combination design requirement.

The objective of this study is to estimate the probability of the simultaneous occurrence of a double-ended quillotine break in the primary loop piping system and an earthquake. A summary report of the large-LOCA-earthquake event combination probability assessment is given by Lu, Streit, and Chou[1]. In this paper the model used for estimating the reliability of piping in nuclear power reactors is presented.

Although initially used to evaluate PWR primary piping, the methodology developed is an advanced computational tool. It can be applied in future evaluations to the break of reactor coolant pipes, large or small, to other PWR and boiling water reactor (BWR) plants, or to general piping reliability assessments. Such studies are clearly beyond the scope of the work reported here, but are part of future phases of the program.

2. APPROACH & MAJOR ASSUMPTIONS

The current practice of considering earthquake and LOCA events acting concurrently generally has been based on conservative engineering judgment that has not addressed the fact that the postulated LOCA and earthquake loads are random events. Amplitude, duration, frequency content, time of occurrence , and time-phase relationship are random and stochastic in nature. Thus, a systematic probabilistic assessment is necessary before a technical basis for an appropriate combination requirement can be developed.

A multiphase, systematic probabilistic approach was used to treat the random nature of earthquakes and LOCAs. In reaching our objective, we took the following steps:

- o Considered many mechanisms that can lead to a pipe failure as a direct result of an earthquake, but concluded that fatigue-crack-growth resulting from the combined effects of thermal, pressure, seismic, and other cyclic loads has the highest potential to lead to complete pipe rupture. Stress corrosion, as a crack growth mechanism, is excluded from consideration because it has not been observed in the primary coolant loops of PWRs. Similarily, the effect of water hammer stress was not included because it has never been observed in PWR primary systems.

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- Modeled fatigue crack growth with a deterministic fracture mechanics model that incorporated stochastic inputs of initial crack size distribution, material properties, stress histories, and leak detection probability. Semi-elliptical internal surface cracks are modeled in the circumferential orientation because of their relation to the postulated double-ended pipe break

- Calculated the probabilities of pipe leaks and breaks during the plant's life by inputing to the fracture mechanics model the results of the stress analysis and estimates of the crack size distribution, material properties, and crack and leak detection probabilities.

3. FRACTURE MECHANICS MODEL

The probability of leak and pipe break is estimated as a function of time for the 40 years of the plant's life. Crack growth and pipe fracture occur only during plant operation as a result of cyclic stresses (thermal expansion, thermal radial gradient, vibration, and seismic). Static stresses (dead weight and pressure) are used to modify the cyclic stress intensity as well as to assess leak and LOCA failure modes.

The calculational procedure for the estimation of leak and guillotine pipe break uses a deterministic fatigue crack growth relation combined with random initial crack size distribution, crack detection probability, material properties, stress histories, and leak detection probability. Figure 1 shows a schematic representation of the calculation procedure.

The fracture mechanics model incorporates many of the advances developed in earlier models, such as those summarized in Refs. 2 - 7. The major extension is the consideration of elliptical defects rather than crack geometries that can be characterized by a single dimension (such as a complete circumferential crack). Hence, a bivariate, rather than a univariate, crack size distribution is required. This added dimension contributes significantly to the difficulty of this problem. However, the model is more realistic, and pipe leaks can be discerned from complete pipe severances. The other major extensions over previous models are detailed consideration of stress gradients through the pipe wall, consideration of leak detection, elastic-plastic and fully plastic failure models, and distributed material properties.

Initial Crack Size Distribution

As-fabricated cracks in piping welds can be either sub-surface or surface. For a given crack size, surface cracks are more severe because they will have a larger stress intensity factor. Based on equivalent crack area and crack length, a surface semi-elliptical flaw has a stress intensity 1.4 to 2.5 times that of an embedded flaw. When this is cast in terms of fatigue behavior, the surface flaw will grow at a rate of 4 to 50 times that of a sub-surface flaw. Interior surface cracks are of more concern than exterior surface cracks, because stresses tend to be higher at the inner pipe wall. This is especially true of radial gradient thermal stress. Hence, attention is focused on semi-elliptical interior surface cracks. It is assumed that such cracks are oriented circumferentially. This is the most severe orientation because they will be normal to the maximum principal stress and can lead to a double-ended pipe break.

The initial crack size distribution is composed of three major parts: (i) the size distribution given that a crack is present, (ii) the probability of a crack being present, and (iii) the probability of detection during pre-service inspection.

The semi-elliptical flaw shape is described by the crack depth, a, and length, 2b. Given that a crack exists, its size (both depth and aspect ratio) was chosen from an appropriate distribution. Based on limited data, the exponential distribution developed by Marshall [8] is used to describe the crack depth distribution in nuclear piping, Fig. 2. This distribution is an upper bound of many distributions suggested in the literature, and its use will be conservative. Very little information was available on the distribution of the crack aspect ratio b/a. We assume, based on observations, that b/a is greater than or equal to one, and use a truncated log-normal distribution to describe its distribution. The mode (most likely value) was chosen to be b/a = 1, and 1% of the cracks were assumed to have an aspect ratio greater than 5. The distribution of aspect ratio is also shown in Fig. 2. Note the small probability of having long cracks (large b/a).

The crack population distribution after pre-service inspection is obtained by multiplying the flaw size distribution by the probability that a flaw exists and that it is not detected. The probability that a flaw exists in a unit volume of weld is taken to be $10^{-4}/in^3$. This value, based on values from earlier studies that are modified to account for the fact that only weld material is analyzed [2,3], is used in a Poisson distribution to estimate the probability a crack is present. Only one crack is modeled in a given joint, and, as such, crack interaction is not considered. The weld volume is taken to also include the heat-affected zone. This will be taken as two wall thicknesses wide.

The as-fabricated crack size distribution is modified by the pre-service inspection and proof tests. The fact that the pipe survived the proof tests allows all cracks of a size large enough to cause failure during the proof test to be removed from the distribution. The influence of pre-service inspection enters through the probability of detecting a defect as a function of its size. This distribution is developed from data available in the literature. Since it is very difficult to detect cracks in welds in cast austenitic stainless steel, a crack half-way through the wall is taken as having a 50% chance of being detected.

Crack Growth Model

The fatigue model for crack growth employs a Paris-type growth rate equation, i.e., $(da/dn) = C(K')^m$. The exponent m and coefficient C were evaluated from the available data [9 - 13]; m is found to be a constant equal to 4, and the coefficient C is log-normally distributed. The median value of C is 9.14×10^{-12} with a standard deviation of 2.20×10^{-11} for K' in units of ksi-in$^{1/2}$ and da/dn in inch/cycle. The expression for K' accounts for the mean stress level by $K' = \Delta\bar{K}/(1 - R)^{1/2}$ where R is the ratio of minimum to maximum stress and $\Delta\bar{K}$ is the cyclic stress intensity factor. Below a threshold value of K' fatigue crack growth is not observed. The fatigue crack growth rate is set to zero when K' drops below the value of 4.6 ksi-in$^{1/2}$.

The semi-elliptical shape of the fatigue crack is assumed to be maintained during crack growth. The size and aspect ratios of the cracks are assumed to be governed by weighted stress intensity solutions K_a and K_b for the depth and length, respectively [14,15]. K_a and K_b are an "rms averaged" stress intensity factor associated with crack growth in the depth and length direction, respectively. The stress intensities are calculated using boundary integral equation techniques [16]. For each class of transient or seismic event (e.g., thermal radial gradient or uniform stress distribution) the maximum change in K for each cycle is used in the fatigue growth evaluation. The values of K_a and K_b for arbitrary stresses on the crack plane are obtainable from influence function which, in turn, are obtainable from the boundary integral equation results for uniform stress. Hence, once the normal stresses on the crack plane for a given transient type are known, the corresponding stress intensitites can be obtained. Results were generated for each transient type, including general results for uniform stresses. To reduce the computation, the stress intensity solution for each transient is evaluated, made nondimensional with respect to flaw size, aspect ratio and stress level, and stored for subsequent use.

Leak and Failure Models

The crack size distribution is updated as a result of the fatigue crack growth. Crack growth can lead to a leak or LOCA or, as in the case of most cracks, result in neither during the plant's life. The leak rate calculation, estimated by two-phase fluid flow analysis, is based on the through wall crack length and the linear-elastic crack opening. The flow length is equal to the pipe wall thickness. The minimum leak size is found to be greater than 2 gpm for the smallest crack, that is for a crack with a length two times the wall thickness and typical piping stresses. Since the required minimum leak detection is 2 gpm, and many leak detection systems are available, we assume all leaks are found and repaired. Although the bivariate crack size distribution is important to assessing the probability of leak, the crack shapes which can lead to the double-ended pipe break without prior leaking are limited to very deep, complete, or nearly complete circumferential cracks. Other large cracks lead to a leak and are detected and repaired prior to growing into a LOCA.

The piping material evaluated in this study is cast 316 stainless steel. Since this material is very tough and ductile its failure will be governed by eastic-plastic fracture concepts or net section plastic instability. For the pipe sizes under consideration, the elastic-plastic fracture models (i.e., J and T) were found to lead to a less critical failure criteria (see paper Division F, 7/3 for details). Using net section plastic instability, we assume that complete pipe severance will occur if the load controlled stresses result in a stress on the remaining ligament which exceeds the material flow stress. For a given applied stress, this defines a portion of the crack size plane which will result in failure. Based on the current crack size distribution, the probability of a break at a given location is simply the probability of having a crack in this portion of the crack size plane.

The flow stress of the material, taken as the average of the yield and ultimate strength, can be considered as either a random variable or fixed value. Information is available in the literature on the statistical distribution of tensile properties of austenitic stainless steel at operating reactor conditions [17-18]. The mean flow stress at the reactor temperature was calculated to be 44.9 ksi, with a corresponding standard deviation of 1.37 ksi. The flow stress was found to be approximately normally distributed.

4. ESTIMATION OF PIPING FAILURE

A computer code was developed to simulate the life history of a reactor coolant piping system including all random elements that dictate a possible pipe rupture. As discussed, these elements include: crack distribution, inspections, loads and stresses, leak detection and material properties. Each weld joint was randomly simulated through all life history replications. The proportion of replications without fractures provided estimates for weld joint reliability. Individual weld joint reliabilities were combined to establish bounds for the system's reliability. Stratified sampling obviated the need for many replications to simulate fractures, which are rare events.

In the succeeding papers we will discuss in detail the simulation procedure (paper Division M #12/3), stress analysis (paper Division M #12/4), and an application of the piping evaluation model to the primary coolant loop of Zion 1 (paper Division J #6/6).

5. CONCLUSIONS

A comprehensive methodology has been developed to estimate the probability of a guillotine pipe break and the simultaneous occurrence of an earthquake. This methodology is the result of an extensive study that encompasses a wide spectrum of the engineering sciences--namely, seismicity, structural mechanics, fracture mechanics, and statistical mathematics. The developed methodology is used to provide an estimate of the probability of a pipe break with and without earthquakes. This methodology also provides, as a by-product, the leak probability for a PWR primary pipe. More importantly, the developed methodology can be applied to the break of reactor coolant pipes, large or small, of other PWR and BWR plants, or to general piping reliability assessments.

Our results (as dicsussed in paper Division J #6/6) are based on assumptions that are clearly stated and discussed in this paper. These assumptions were necessary and reflect our best judgment based on technical information available from the literature and some preliminary analyses. They have been reviewed by technical experts in the related fields, and they will be subject to further review.

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8. FIGURE CAPTIONS

Fig. 1 Schematic representation of the calculational procedure used in the fracture mechanics analysis of reactor piping reliability.

Fig. 2 Marginal distribution of initial crack depth, a, and aspect ratio, b/a, given that a crack exists. The crack depth distribution is taken from Marshall [2] whereas, the distribution on aspect ratio was developed from available information.

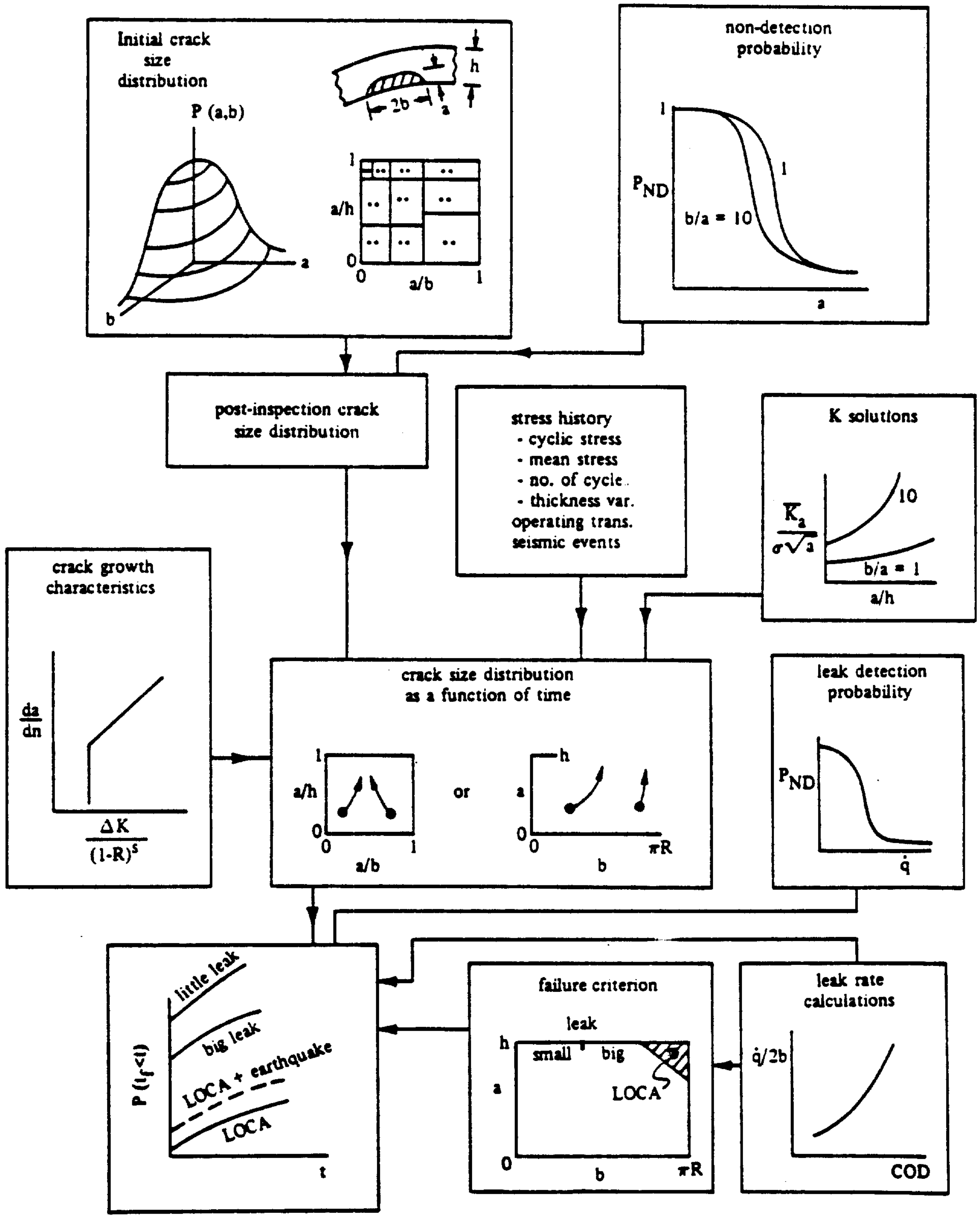
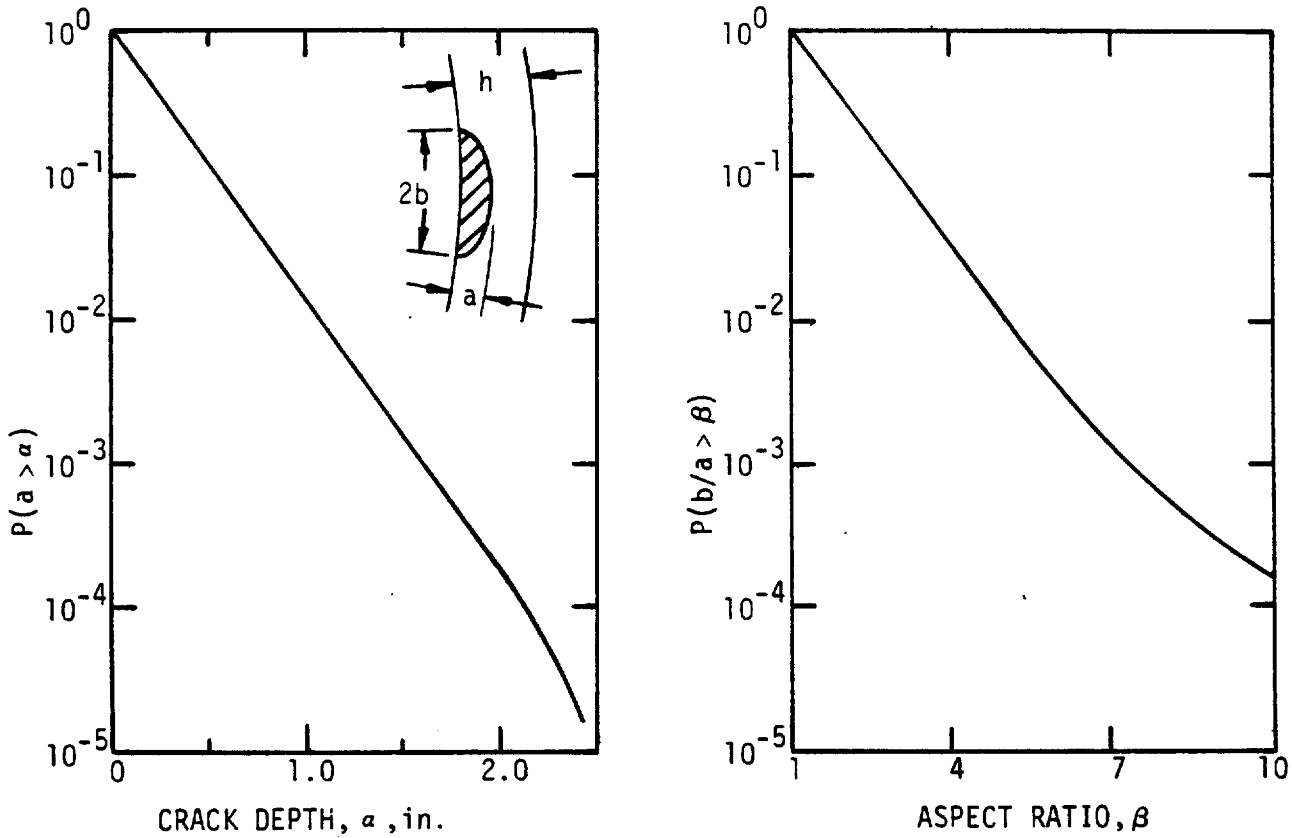

Initial crack size distribution
P (a,b)
a
b
h
2b
a
1
a/h
0
0
a/b
1
non-detection probability
1
P_{ND}
1
b/a = 10
a
post-inspection crack size distribution
stress history
- cyclic stress
- mean stress
- no. of cycle
- thickness var.
operating trans.
seismic events
K solutions
$\frac{K_a}{\sigma\sqrt{a}}$
10
b/a = 1
a/h
crack growth characteristics
$\frac{da}{dn}$
$\frac{\Delta K}{(1-R)^s}$
crack size distribution as a function of time
1
a/h
0
0
a/b
1
or
h
a
0
0
b
πR
leak detection probability
P_{ND}
$\dot{q}$
little leak
big leak
LOCA + earthquake
LOCA
t
failure criterion
leak
small
big
h
a
LOCA
0
b
πR
leak rate calculations
$\dot{q}/2b$
COD

FIGURE 1



10^0
10^-1
10^-2
10^-3
10^-4
10^-5
P(a > a)
h
2b
a
0
1.0
2.0
CRACK DEPTH, a ,in.
P(b/a > β)
1
4
7
10
ASPECT RATIO, β

FIGURE 2